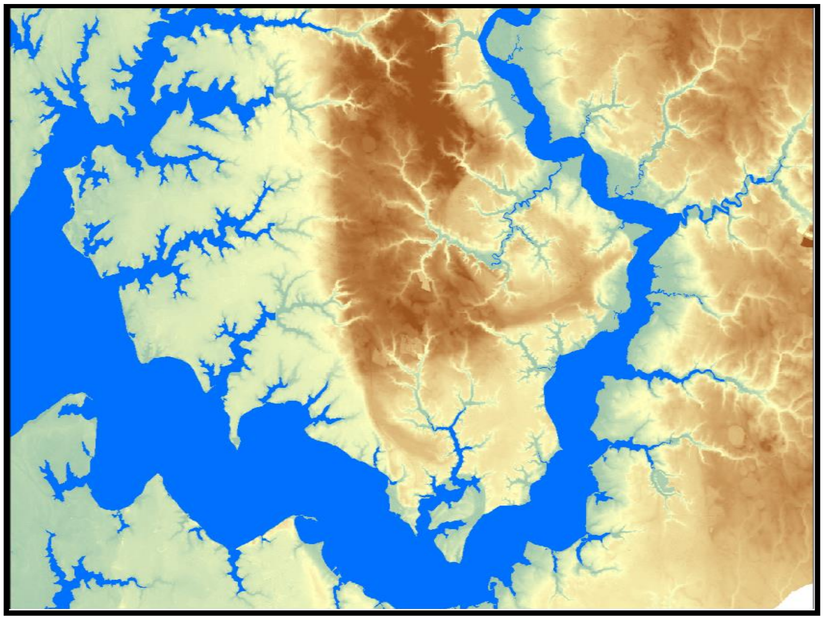
Revisiting Coastal Land-Water Interactions: The Triblet Connection



STAC Workshop Report
May 23-24, 2018
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About the Scientific and Technical Advisory Committee

The Scientific and Technical Advisory Committee (STAC) provides scientific and technical guidance to the Chesapeake Bay Program (CBP) on measures to restore and protect the Chesapeake Bay. Since its creation in December 1984, STAC has worked to enhance scientific communication and outreach throughout the Chesapeake Bay Watershed and beyond. STAC provides scientific and technical advice in various ways, including (1) technical reports and papers, (2) discussion groups, (3) assistance in organizing merit reviews of CBP programs and projects, (4) technical workshops, and (5) interaction between STAC members and the CBP. Through professional and academic contacts and organizational networks of its members, STAC ensures close cooperation among and between the various research institutions and management agencies represented in the Watershed. For additional information about STAC, please visit the STAC website at http://www.chesapeake.org/stac.

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Contents

Executive Summary

In response to stakeholder concerns regarding where best to target advanced management practices to benefit shallow waters resources, the Chesapeake Bay Program's (CBP) Scientific and Technical Advisory Committee (STAC) convened a workshop in May 2018 to explore the utility of a triblet-based approach to watershed management. Currently, county planners and watershed coalitions rely on county-based pollution nutrient and sediment reduction targets to guide restoration plans. The CBP model segmentation strategy provides some additional guidance to highlight sub-county areas identified as having a disproportionate impact on the health of Bay system. Briefly, this CBP map layer was developed by intersecting major tributary catchment delineations with county municipal boundaries. Stakeholders, however, expressed concerns that this framework does not provide adequate guidance to identify where focused restoration efforts can best yield measurable benefits to living resources. More importantly, the "land-river segments" do not provide an intuitive basis to promote local understanding of where or how human activities influence coastal conditions. From a research perspective, modern field surveys reveal smaller tributaries to the mainstem tributaries (e.g., Choptank or Severn River systems), or triblets, may provide a more effective basis for studying terrestrial-estuarine linkages. These smaller waterways vary widely in water quality and habitat condition and also influence on the broader estuarine system. Further, coastal resources of concern and human activity concentrate along these triblets, yet these distinct landscape elements remain undervalued and understudied.

The workshop provided an opportunity to evaluate whether the triblet concept provides a useful basis for informing watershed management and advancing coastal research. Thirty (30) participants with cross-disciplinary expertise in watershed hydrology, estuarine circulation, biogeochemistry, systems modeling, restoration management, and behavioral-economics participated in the two-day discussion hosted by Hood College's Center for Coastal and Watershed Studies.

Participants unanimously agreed that the triblet concept provides a powerful framework to connect Bay stakeholders with the Chesapeake Bay Program and the science community. Although the precise definition of a triblet remained somewhat elusive, all agreed that triblets refer to open-water channel corridors that flow through the terrestrial-estuarine transition zone, or T-zone, and connect the T-zone to its full catchment. The T-zone concept is adopted from the San Francisco Bay community. **The T-zone includes "the area of existing and predicted future interactions among tidal and terrestrial or fluvial processes that result in mosaics of habitat types, assemblages of plant and animal species, and sets of ecosystem services that are distinct from those of adjoining estuarine, riverine, or terrestrial ecosystems"** (Goals Project 2015). It extends landward, through the limits of tidal effects on terrestrial and fluvial conditions, and seaward, to the limits of the effects of terrestrial runoff and other freshwater discharges on estuarine conditions. Importantly, the boundary of the T-zone extends much farther inland than coastal wetland-upland boundaries, to where base level conditions (e.g., sea level) influence water table position and ground- and surface-water exchange. **Triblets refer to natural channels within the T-zone that connect uplands to coastal waters. Triblets function as natural bioreactors that regulate interactions between terrestrial discharge and oceanic inflows and modulate impacts from terrestrial land use and coastal management.** The challenge of defining triblets more specifically reflected different ideas regarding the appropriate spatial scale for defining these critical landscape elements. Workshop participants could agree that triblets typically have catchment areas less than 5,000 ha (20 square miles) and cross-sectional, open-water widths of less than 100 m.

A significant portion of the workshop focused on sharing insights to understand better the role of triblets as bioreactors affecting the exchange between upland and coastal waters. Discussions highlighted the importance of basin morphometry, orientation to the mainstem currents and prevailing winds, and watershed condition, all of which control hydrochemical gradients and residence time within a triblet and its estuary. Triblet conditions affect terrestrial-aquatic habitat quality, wetland function, and water quality conditions related to public health concerns throughout the entire T-zone. Like river corridors, triblet hydrobiogeochemical dynamics occur longitudinally along the channel and also laterally, between the triblet channel and adjacent land areas.

Based on the discussion, workshop participants developed the following recommendations for promoting science-based watershed and coastal management:

- Establish objectives and define targets for advanced management based on triblet units. A range of stakeholder concerns, in addition to water quality, influence watershed management and resource allocations for restoring the Bay. Stakeholder concerns, including their understanding of system dynamics, must be incorporated when defining and evaluating management alternatives. Indicators and measurable targets should reflect these concerns. A comprehensive approach to stakeholder engagement could advance CBP goals more effectively.

- Identify high-priority triblet catchments where comprehensive management can provide maximum, measurable benefits to water quality, habitat, and living resources. Ideally, this information would include high-resolution maps of triblet conditions, and a summary of expected system response(s) to management actions (i.e., spatially-explicit model predictions).

- Select integrated practices in one or more strategic locations to restore *processes* (e.g., hydrologic exchange within the triblet corridor) rather than *habitat*. Improving triblet condition requires a comprehensive suite of watershed, shoreline, and in-channel practices to reduce flow constrictions and restore natural environmental flows.

- Advance field research i) to improve our capacity to predict how triblet systems respond to a broad range of management actions, and ii) to increase stakeholder adoption of advanced management practices.

More detailed recommendations are outlined later in this report.

Conclusions from this workshop also are relevant to the Bay Program's modeling strategy. The following recommendations are intended to improve the relevance of CBP's guidance to managers and to address concerns with the model structure

- **Refine the CBP model segmentation strategy to reflect the importance of the T-zone and triblet corridor management.**

- **Focus modeling and management efforts on the terrestrial-estuarine transition zone.**

Evidence from this workshop and recent literature (e.g., Xenopoulos *et al*. 2017; Collins *et al*. 2015), highlight the importance of the transition zones, both in terms of functioning as bioreactors that potentially moderate or alter impacts from upland catchments and as critical habitat for coastal resources of concern (e.g., oysters and crabs, nursery habitat for fisheries, and river/marine recreation and tourism).

Workshop Overview:

Restoring the Chesapeake Bay has mainly focused on the major rivers to the Bay system and estuarine processes along the mainstem of the Bay (Figure 1). Stakeholders, however, are increasingly concerned with their local waterways and degraded shallow water habitat along nearly 12,000 miles of shoreline. There also is increasing concern regarding the influence of small- to medium-sized waterways on the Bay's major tributaries. Monitoring data reveal widely varying water quality conditions and impacts to coastal ecosystem services among these nested tributaries, due primarily to human activities (Morse et al. 2013). For example, mean dissolved oxygen concentrations based on weekly surveys ranged from 0 to 10 mg/L among ten triblets to the South River (Muller and Muller 2014) and among similar-sized tributaries in other East Coast estuarine systems (Keppler et al. 2015; Lerberg et al. 2000). While we can document variation in triblet condition, we have less understanding of factors affecting triblet condition and how triblet condition influences shallow Bay habitat. To address these knowledge gaps, the Chesapeake Bay Program's (CBP) Scientific and Technical Advisory Committee (STAC) sponsored a two-day workshop, "Revisiting Coastal Land-Water Interactions: The Triblet Connection," held on May 23-23, 2018, at Hood College in Frederick MD. Participants provided cross-disciplinary expertise in watershed hydrology, estuarine circulation, biogeochemistry, systems modeling, restoration management, and behavioral-economics to explore whether triblets provide a more useful framework for watershed and coastal management than the existing CBP segmentation strategy and modeling framework.

Workshop Objectives:

- Define triblets and evaluate their relevance for restoring the Chesapeake Bay.
- Develop a conceptual model(s) to describe triblet-tributary interactions and to guide triblet management-based condition and influence on Bay resources of concern.
- Outline recommendations to advance Bay watershed management, based on triblet function.
- Identify critical information gaps and research opportunities to advance restoration of the Chesapeake Bay through triblet watershed and coastal management.

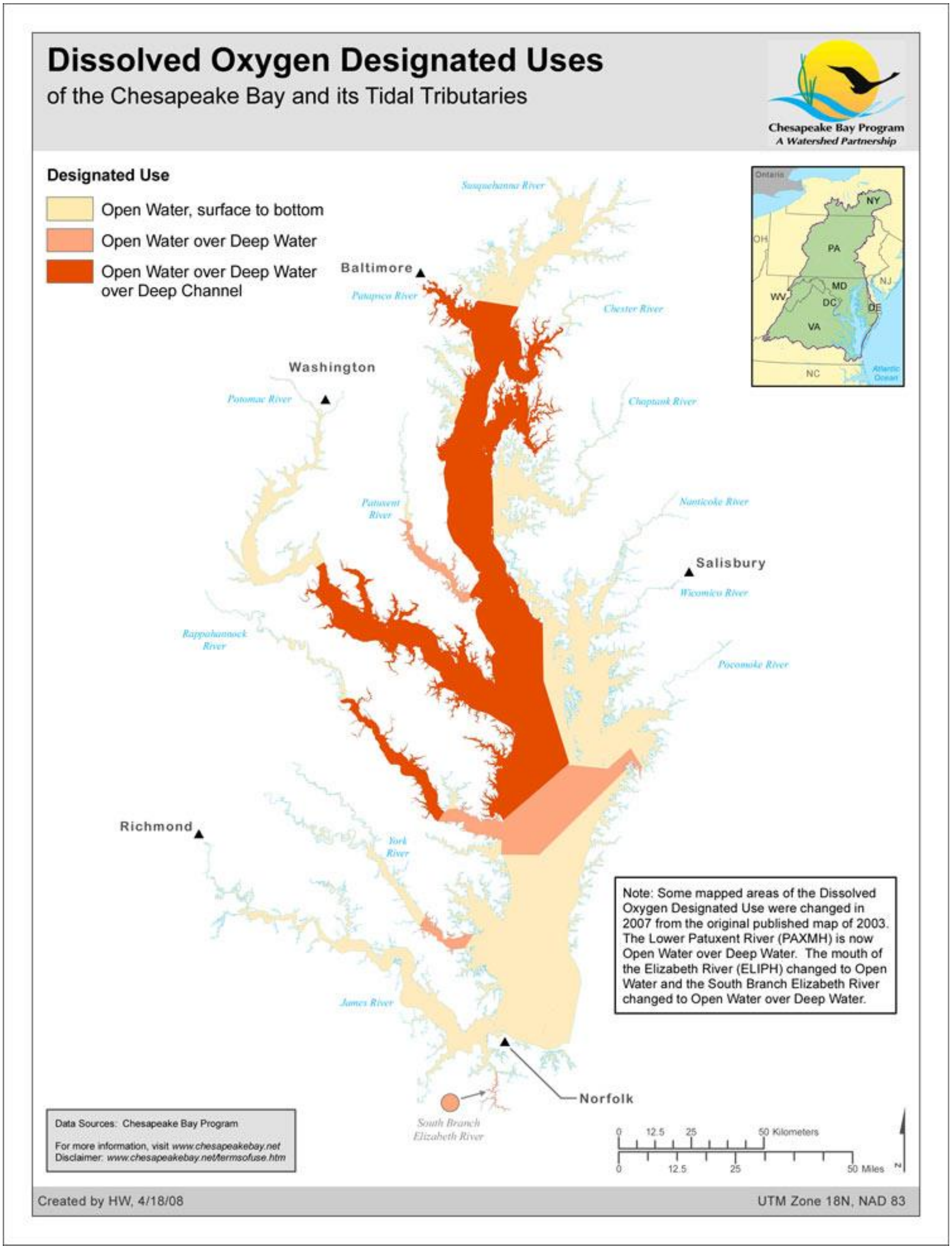

Figure 1. Major rivers and designation of Bay segments represented in the Chesapeake Bay Program's regulatory watershed model. Source: https://www.chesapeakebay.net/what/maps/dissolved_oxygen_designated_uses_of_the_chesapeake_bay_and_its_tidal_tribut; accessed 5/9/2018.

The Trouble with Triblets

How do (or should) we define triblets?

Workshop participants unanimously agreed there is an urgent need to raise awareness regarding the role of triblets in amplifying human terrestrial impacts and disproportionately affecting coastal resources. It was difficult, however, for experts to settle on an explicit definition of triblets. This challenge reflected the broad range of disciplines represented in the discussion, and the reality that triblets come in many sizes, shapes, and forms: No two triblets are the same. The challenge also reflected the lack of research describing complex interactions that occur in these transition zones between non-tidal uplands and downstream estuaries. In developing the definition, participants considered the need for identifying triblets as critical landscape elements requiring additional studies to understand the biophysical significance of these landscape components.

Defining triblets: Reconciling spatial scales

Various ideas emerged regarding the appropriate size and resolution with which to define triblets (Figures 2 and 3). Some considered triblets the same as tidal creeks, typically less than 100 m wide, whereas others proposed triblets should refer to small- and medium-sized natural waterways connecting upland areas to estuaries. This latter approach would result in hundreds of catchments along each major tributary of the Chesapeake Bay, each typically 15 to 25 square miles in area. The coarsest scale proposed defining a triblet as a distinct body of water enclosed by a shoreline with a distinct local watershed and mouth to the Bay system. Regardless of scale, all definitions highlighted the critical role of small-sized tributaries affecting Bay resources of concern. This framework contrasts the CBP modeling framework, which focuses on the mainstem of major tributaries to the regional Chesapeake Bay system.

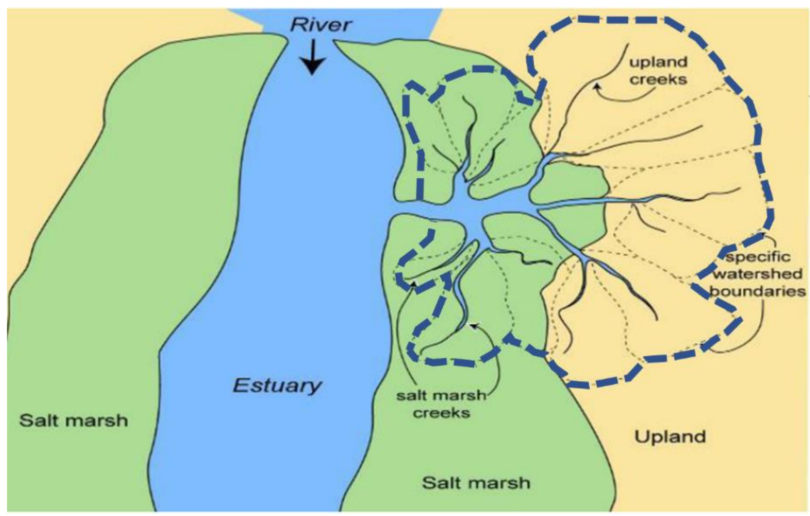

Figure 2: *Estuarine system components related to defining triblets (modified from Sanger's presentation). Workshop participants ultimately agreed that triblets represent systems larger than salt marsh creeks, including upland areas that represent terrestrial-estuarine linkages. The scale of a triblet's definition remained challenging, with some preferring to include all the salt marshes and contributing catchments to small bodies of water with distinct shorelines and mouths feeding to a larger estuarine system.*

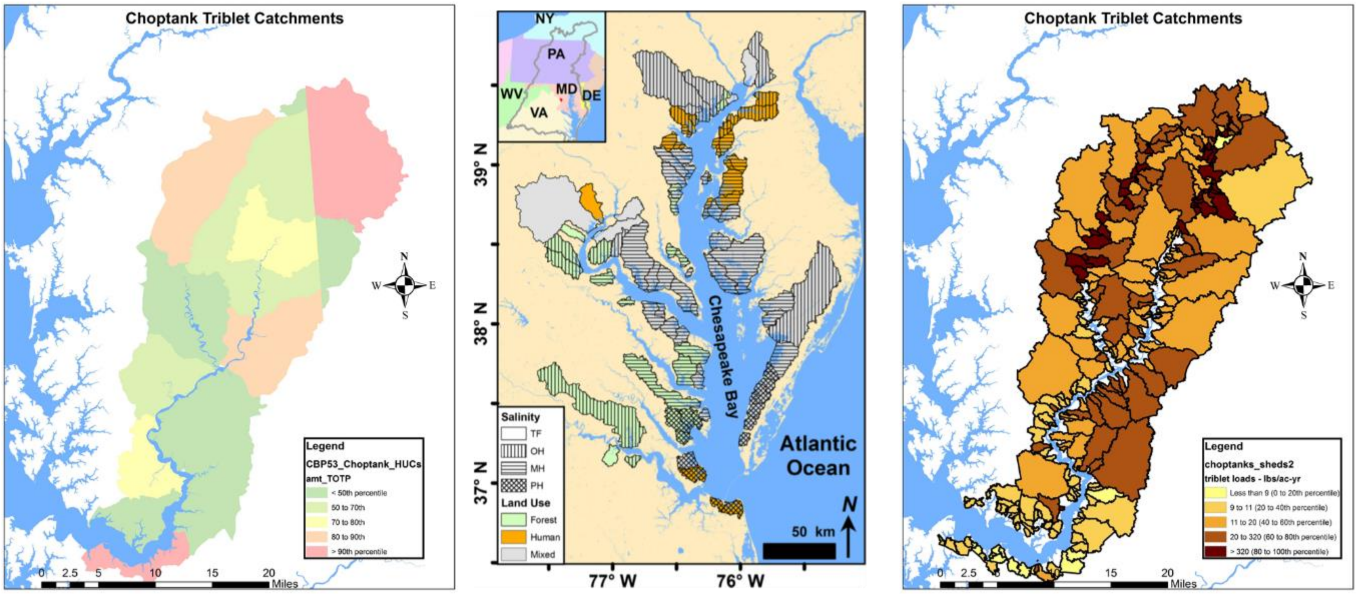

Figure 3: *Current Chesapeake Bay Program's land-river model segments of the Choptank River in contrast to potential triblet-based model segmentation strategies, including land areas draining to small estuaries (middle) or based on channelized waterways connecting uplands to the estuary (right). Note the middle figure maps examples of triblet catchments across the Chesapeake Bay watershed (Weller and Jordan), in addition to the Choptank River subsystems (left and right panels).*

The terrestrial-estuarine transition zone, or T-zone, has emerged as a robust framework to manage watershed-estuarine linkages. Defined initially for the San Francisco Bay estuary (Goals Project 2015), the **T-zone refers to "the area of *existing and predicted future* interactions among tidal and terrestrial or fluvial processes that result in mosaics of habitat types, assemblages of plant and animal species, and sets of ecosystem services that are distinct from those of adjoining estuarine, riverine, or terrestrial ecosystems."** It extends landward, through the limits of tidal effects on terrestrial and fluvial conditions, and seaward, to the limits of the effects of terrestrial runoff and other freshwater discharges on estuarine conditions. Importantly, the boundary of the T-zone extends much farther inland than coastal wetland-upland boundaries to where base level conditions (e.g., sea level) influence water table position and ground- and surface-water exchange. Along triblet waterways, this up-gradient boundary, based on elevation, coincides with the freshwater micro-tidal zone during tidal anomalies. The extent of the T-zone is influenced by the vertical range of the tide, topographic relief of the catchment and its waterways, and geology. In the downstream direction, the T-zone can extend beyond the mouth of the triblet or tributary and mainly depends on the volume of terrestrial runoff relative to oceanic influence. Like river corridors, hydrologic exchange occurs longitudinally and laterally along the triblet channel. Triblets represent a critical element of the T-zone because these waterways regulate impacts from up-gradient land use, shoreline management, as well as sea-level fluctuations on coastal resources, including but not limited to shellfish habitat, fish spawning habitat, wetlands that provide flood and shoreline protection, and water quality conditions affecting public health risks.

Definition of triblet (noun)

A waterway and its adjacent floodplain corridor that flows through the terrestrial–estuarine transition zone and connects uplands to coastal waters. A triblet functions as a natural bioreactor that regulates interactions between terrestrial discharge and oceanic inflows and modulates impacts from terrestrial land use and coastal management. Triblets typically have catchment areas less than 5,000 ha (20 square miles) and cross-sectional, open-water channel widths of less than 100 m.

Key factors affecting form and function of triblets and triblet corridors

Experts expected the same drivers that affect circulation patterns in the mainstem of the Chesapeake Bay and its major tributary estuaries to also influence nested triblets systems (Testa et al. 2017): Triblet form and function largely depends upon tidal interactions within an estuary's mainstem controlled by the volume and timing of watershed discharge relative to tidal fluxes. The strength and extent of these exchanges are controlled by a triblet's hydrogeologic setting, which includes its basin morphometry, basin geology, and triblet orientation to tidal and wind forces. Human impacts, including watershed and groundwater management, shoreline disturbances, and channel modifications, are superimposed upon a triblet's natural setting. Depending on the size of the triblet and scale of human impacts, alterations strongly affect a triblet corridor's form and function.

Tidal Exchange

Estuaries historically have been classified based on a characterization of a system's typical fresh- and oceanic water interactions that affect hydrochemical gradients across the system, and triblets likely can be classified similarly. In a well-mixed system, the saltwater-freshwater interface moves up and down the longitudinal axis of the estuary as a vertical front. In less well-mixed systems, saltwater wedges form where riverine or oceanic inputs predominantly influence hydrologic exchange. The location and intensity of a salt wedge varies across space and time, depending upon seasonal and short-term weather patterns. Major storm events with excessive freshwater discharge during warm seasons typically have the most significant potential for stratification. Salt plug systems represent the third class of estuaries usually associated with tropical climates. Here, long durations of heat and low precipitation lead to dense, hypersaline waters settling in deep pockets and forming a plug that isolates deep waters from estuary circulation. In Chesapeake Bay triblets, salt plugs form through a different mechanism: Freshwater discharge delivered from a triblet catchment and the mainstem of the major tributary trap saltwater in the mid- to lower estuary, to form the plug or hypoxic squeeze which limits exchange between the nested systems.

The extent of tidal exchange strongly affects an estuary's potential for eutrophication. Well-mixed systems have the least potential for horizontal stratification or stagnation of triblet waters and, therefore, less potential to develop anoxic conditions and degraded water quality. Triblet systems susceptible to developing severe salt wedges or salt plugs, especially in drier months when denser salt waters may intrude further upstream, have the highest potential to develop eutrophic conditions and degraded water quality.

Basin Morphometry

As found in larger estuarine systems, triblet tidal ranges and circulations are influenced strongly by system geometry, including shape, depth, and size. Tidal fluctuations and impacts from tidal anomalies are more significant in confined estuaries with larger length-to-width ratios than in broader, more open systems where tidal extremes progress gradually through the system (i.e., progressive wave system). In narrow, more constrained estuaries, tidal extremes occur at the same time throughout the entire estuarine system, as a standing-wave system, and there is no flow during tidal extremes. In a perfect standing wave system, opposing waves have the same amplitude and wavelength. These conditions occur where tidal and reflected waves cause interference, more typically in estuaries with narrow inlets and channels. Alluvial estuarine systems, such as those of the Chesapeake Bay, do not occur as one extreme or the other but behave in an intermediate or mixed state between a progressive and standing wave system. The predominant state shifts among sub-estuarine systems along the Bay's main stem (Ahnert 1964). Near the mouth of the Bay, tidal currents enter as progressive waves but evolve into standing waves as the current moves up the estuary and into the smaller sub-estuaries. Small-scale harmonics become more critical as one moves up the tributary, leading to either hypo- or hyper-synchronous systems (so-called "M4" and "M6" tides). The lag time generated by increased friction in more shallow and constrained estuaries (and triblet sub-estuaries) affects the timing of tidal exchange throughout the entire triblet corridor, which affects sediment transport and deposition throughout an estuarine system (Dronkers et al., 1986). While we understand that tidal dynamics influence hydrobiogeochemical processes across an estuarine system, there was less certainty with using these characteristics to evaluate triblet vulnerability to degradation and also triblet influence on the broader (i.e., larger-scaled or mainstem) estuarine system.

The shape or meandering of the triblet channel can be indicative of the tidal exchange and residence time (Ahnert 1964). Processes that shape estuarine geomorphology differ from fluvial systems despite producing similar meanders. Estuarine meanders form where the maximum currents occur between low and high tide (i.e., standing wave systems) when the lateral erosion is most effective in-between tidal extremes. Meanders also form more commonly where watershed and tidal flows are similar, whereas straighter channels occur where watershed discharge predominates the overflow regime (Figure 4).

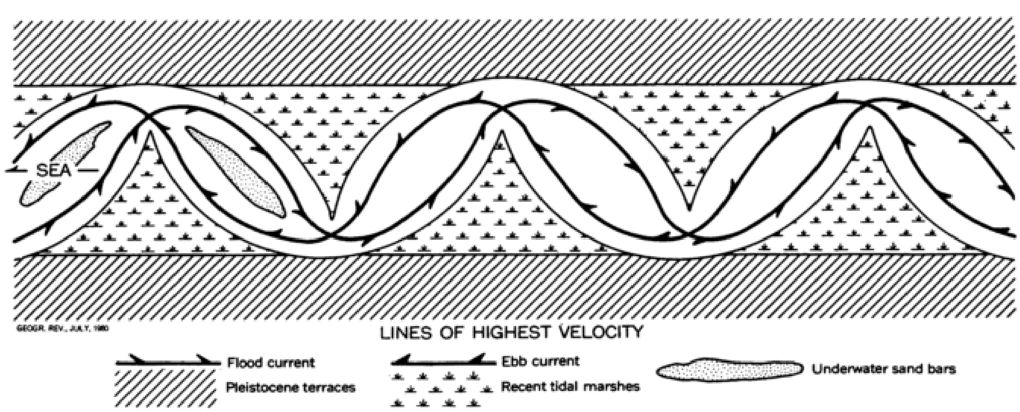

Figure 4. Schematic diagram of triblet/estuarine meander, highlighting the importance of the balance between watershed discharge and tidal influence (Ahnert 1964).

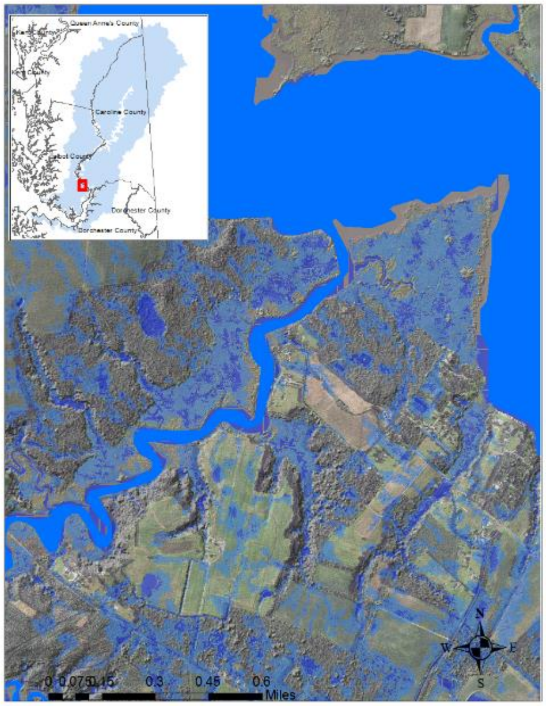

__Figure 5.__ Examples of meandering versus straight triblets within the Choptank River system.

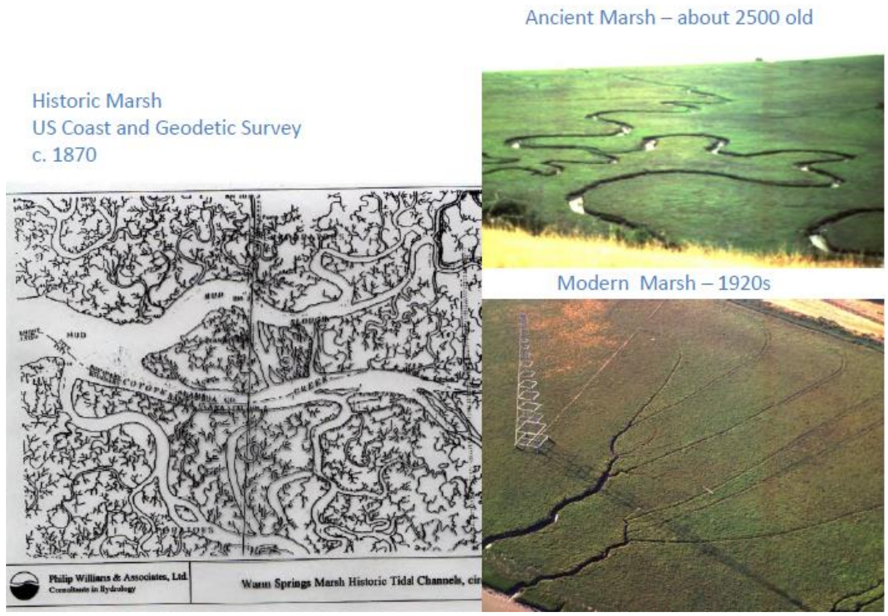

__Figure 6.__ Transformation of estuarine tidal creeks in the San Francisco Bay during the 20th Century. (From Goals Project 2015)

Indeed, the extent of meandering among triblets to the Chesapeake Bay vary greatly, perhaps suggesting that some sub-catchments have more direct connections with the Bay mainstem and its major tributaries (Figure 5). Also relevant to this hypothesis, it is interesting to note that up until the 20th century, ancient marshes (approximately 2,500 years old) in the San Francisco Bay region had more meandering forms than modern-day triblets (Figure 6), perhaps suggesting impacts from profoundly altered or hardened catchment conditions.

Bathymetry

The bathymetry of an estuary influences turnover or water residence time by affecting the strength of the inflows and the potential for backflow or counter-currents to form. More variable relief across the estuarine floor or bottom roughness creates more friction and can affect tidal exchange. Deep pockets, shoals, and entrenched navigation channels have been found to significantly influence circulation patterns and hydrologic exchange across the Bay's tributaries.

Coastline Configuration

Coastline complexity can influence tidal exchange as well as the potential for shoreline erosion. Complex shorelines create more friction than smooth or hardened shorelines and, therefore, can dampen upstream tidal influence, thus highlighting the importance of shoreline management.

Wind, Atmospheric Forcing and Wave Effects

Wind modulates tidal currents and waves significantly enough to alter estuarine circulation and shoreline sediment dynamics. For example, winds moving parallel to the longitudinal axis of a triblet can increase or decrease tidal flows and affect salinity gradients (Scully 2010). The most potent effects occur when winds align with the thalweg (i.e., a line connecting the lowest points of successive cross-sections along the channel mainstem) of an estuary, creating a stronger potential for turnover of deep, potentially anoxic waters. There is less potential for turnover when winds blow perpendicular to the thalweg toward shallow shoals more distant from deep waters. A triblet's orientation to predominant winds may influence its susceptibility to degraded conditions.

Wind-driven waves can have a more significant influence on currents, water exchange, and water quality than wind-driven circulation (Delpey et al. 2014). Riverine discharge during storm events tends to spill over an estuary, overlying inflowing salt waters, but wave energy combined with the tidal exchange can limit that outflow through the lower estuary. More importantly, waves provide a primary force resuspending bottom sediments (Colman et al. 1992).

Temperature

Temperature conditions provide a key but often overlooked control on biotic processes across estuarine systems. Elevated brackish water temperatures can increase the proliferation of harmful algae and bacteria blooms, as well as various life stages of highly valued Bay species (Mulholland et al. 2009). For example, in the Sassafrass and James Rivers, late summer freshwater cyanobacteria blooms were associated with surface water temperatures in triblets exceeding 25 °C, especially after rain events (Leight et al. 2015). Likewise, low dissolved oxygen conditions in the South River and Severn River systems, related more to temperature rather than salinity-driven stratification. While temperature extremes are driven mainly by estuarine exchange and direct solar radiation, thermal pollution has been linked to riverine discharge, especially in catchments with expansive impervious surface areas (i.e., urban heat centers). Historical data, however, lack the spatial resolution to untangle the relative influence of human versus natural control on estuarine temperature regimes. Existing data highlight detrimental effects associated with extreme temperature gradients within a triblet system, but the few cross-system studies limit our capacity to understand underlying controls.

Carbon Dynamics

External carbon (C) supplies combined with internal production dynamics represents a critical and perhaps overlooked driver of estuarine condition. Because the regulatory framework for the Bay watershed focuses on nutrients and sediment, there is limited attention focused on how human activity affects carbon supply to coastal systems. Impacts from excess carbon loads, however, may pose equally severe risks to environmental water quality and triblet condition. Depending on the form and concentration, elevated dissolved organic carbon (DOC) fluxes can affect food web structure, the mobility of metals, and physio-chemical parameters critical to habitat condition. For example, cyanobacterial blooms are linked to high terrestrial (allochthonous) carbon loads and fertilizer application (King et al. 2017; Xu et al. 2015). Despite the critical role of C in estuarine systems (Redfield 1958), we have limited understanding of where excess carbon loads originate or how different sources of dissolved organic matter might influence estuarine conditions.

Both the quantity and quality of terrestrial carbon influence estuarine condition through a cascade of effects tied to plant production and decomposition rates. Carbon quality varies widely, depending upon its source. The most labile carbon (G1 class) generally is produced internally, and most prolifically where temperature, light penetration, and available nutrients enhance phytoplankton and benthic algae production. This primary production may be highest in broad, shallow tribulates with more expansive light penetration. Under eutrophic conditions, internal overproduction of labile carbon leads to low oxygen conditions because of enhanced microbial respiration and effects on redox condition. Moderately labile C (G2 class) includes new terrestrial organic matter, wetland organic matter, and submerged aquatic vegetation remnants. The most recalcitrant C (G3 class) consists of weathered terrestrial organic matter, such as coal and wood. Older, more recalcitrant carbon sources primarily affect turbidity and have a less direct influence on estuarine biogeochemical processes tied to decomposition. When the supply of labile carbon is limited, however, elevated nutrients with steep hydrochemical gradients can increase the importance of recalcitrant carbon to microbial respiration and aquatic decomposition. These conditions likely occur in triblet segments where there is limited circulation, and there are longer residence times. Compared to our understanding of nutrient and sediment dynamics, there has been relatively little focus on the form and function of terrestrial carbon fluxes and its influence on estuarine condition. Like nutrients and sediment, it is critical to understand the bioreactivity of the widely varying range of carbon compounds as well as to identify and manage excess carbon sources.

Human Alterations and Impacts

As we refine our characterization of human activities throughout the Bay watershed using more detailed spatial data, a better understanding of sub-estuarine systems responses continues to emerge. High-resolution topography and land use, land cover data highlight 1000’s of miles of artificial drainage, expansive impervious surface coverage, and agricultural and construction areas. The watershed hardening effect has altered the timing and magnitude of freshwater inputs to tributaries and the Bay’s mainstem significantly. Extreme precipitation events generate more floodwaters with higher concentrations of nutrients, sediment, organic matter, and other contaminants of concern. Degraded freshwaters deluges contribute to declining sub-estuarine conditions (Wetz and Yoskowitz 2013). Indeed, sediment cores indicate that human land-use patterns since the early 1700s have led to a downstream shift of salinity gradients along the Bay’s tributaries despite rising sea level, especially to the north of the Bay system where more intensive human activities occur (Sowers and Brush 2014). Increased turbidity and enriched nutrient regimes limit seagrass production while exacerbating harmful algal blooms. Degraded watershed conditions also contribute to drought impacts. With increased runoff also comes decreased inter-storm baseflow. Under drought conditions, more limited surface water supplies combined with extensive groundwater extraction has led to intensified and more frequent low freshwater inflows (Wetz and Yoskowitz 2013), which significantly alters estuarine circulation patterns and may increase stratification, especially in the more sensitive triblets (Muller and Muller 2014). The most substantial evidence of adverse human impacts tends to occur in headwater reaches (i.e., zero- and first-order streams) of the T-zone. These observations are consistent with those in non-tidal areas as well.

Shoreline development presents another set of impacts to estuarine exchange, water quality, and coastal habitat condition. Armoring reduces the resiliency of submerged aquatic vegetation and native species and also enhances the establishment of invasive species (Chambers et al. 1999; Peterson et al. 2000; Patrick et al. 2014). The multiple benefits of living shorelines have created relatively keen interest among coastal residents and resulted in some of the more successful habitat restoration programs, to date. As sea-level rise continues, however, increased habitat fragmentation and limited habitat migration potential continue to challenge coastal restoration managers (Peterson and Lowe 2009). The proliferation of private docks and boating activity along triblet corridors presents another set of less visible concerns. Sediment agitation caused by vessel movement and propeller wash increases suspended sediments, thus increasing its reactivity and releasing nutrients and bacterial and harmful algal resting stages while also reducing water clarity (Roberts 2012). These activities generally occur during extreme (warm) summer conditions, when elevated water temperatures can enhance microbial activity and exacerbate poor water quality.

Dredging and artificial channelization of open waters throughout the triblet corridor presents a third, often-overlooked set of human impacts on Bay tributary and triblet systems. Modified bathymetry affects tidal ranges, freshet delivery and saltwater intrusion, and both lateral and longitudinal hydrochemical exchange (Meyers et al. 2014). Navigation channels influence estuarine turbidity maximum dynamics by concentrating freshwater discharge and oceanic inflow along a narrow, deep “pipe,” effectively altering triblet hydrochemical gradients (Chant et al. 2018). In the upper T-zone, channel straightening, hardening, and incision short-circuits natural biogeochemical processes to reduce both water storage and water quality benefits provided by the triblet corridor. For example, along the Pocomoke River, confining the tidal exchange to an entrenched and straightened river corridor limits lateral exchange with adjacent floodplains (Noe et al. 2019; Kroes and Hupp 2010; Hupp et al. 2009). During extreme surge events, extensive dredging and straightening of the river channel likely result in flooding further inland than if more natural lateral exchange occurred, thus potentially increasing the upstream extent and impacts of tidal anomalies.

Finally, human infrastructure can create important pinch points and barriers that significantly influence estuarine circulation. For example, bridge pilings may alter local circulation patterns, including vortices and wakes around pilings, that influence sedimentation and water quality processes (Ye et al. 2018).

Climate Change Effects:

In the Mid-Atlantic region, predicted weather patterns over the next 20 to 50 years include temperature increases by one to three degrees Celsius; annual precipitation increases between 10 and 20 cm, with higher evapotranspiration during the summer and wetter winter conditions; and more frequent extreme storms with more than 2.5 cm precipitation per event (Kunkel et al. 2013a and b). The altered weather regime likely will increase runoff (Ross and Najjar 2019) and evapotranspiration, especially in hardened watersheds, and thus affect stream hydrology by increasing peak storm flows and reducing intervening baseflow conditions (Figure 7). Hardened watersheds refer to areas where expansive impervious surfaces or historical agricultural practices have increased surface water runoff by reducing infiltration, resulting in flashier stream and river systems. Since triblet catchments include a high proportion of shallow waters bordered by development, shifting weather patterns likely will have a disproportionate effect on these systems.

By 2100, sea levels across the Upper Chesapeake Bay will increase by 0.65 to 1.25 m and tidal range will increase by up to 10 cm/m (Ross et al. 2017) (see Figure 7). The combined effects of these factors, along with increased watershed discharge, likely will lead to cascading effects on estuarine processes, especially in triblets. For example, sea-level rise will cause higher fractional increases in water depth in shallow triblets compared to larger tributaries and likely increase the length of saltwater intrusion along the hydrologic gradient more significantly. Biological effects also are likely. For example, the occurrence and timing of harmful algae blooms linked to urban development suggest more frequent coastal flooding will increase the potential for blooms to develop and migrate from triblets to the larger estuarine system. The elevated sensitivity of triblets to changing sea levels and shifting weather patterns highlights the importance of managing triblets and triblet catchment.

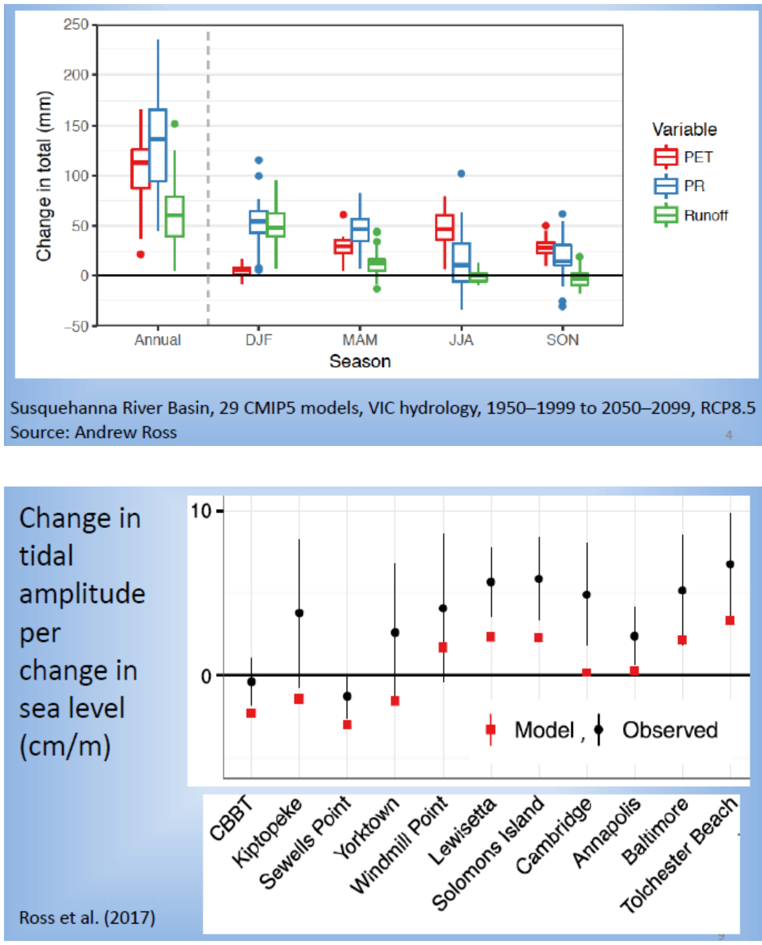

__Figure 7.__ Predicted climate change effects in the Chesapeake Bay region, including A) shifting hydrologic conditions (Modified from Ross et al 2015); and B) increased tidal range. Legend descriptions: PET – potential evapotranspiration; and PR – precipitation (Modified from Ross et al 2017).

Modeling Triblet Function and Predicting Management Response:

Limited resources for restoration highlight an urgent need to compare triblet conditions across the Bay and to predict how a triblet will respond to management actions. The complexity and diversity among the Bay's hundreds of triblets even within a single major tributary's catchment, however, presents significant challenges to modeling these nested sub-systems. For example, estimating the residence time and potential to develop poor water quality conditions remain challenging. The participants discussed existing, simple estuarine characterizations that may provide a useful metric for comparing triblets. These included tidal prisms and flow return indices as first-order indicators of residence time and susceptibility to eutrophication. Only management actions that affect a system's residence time directly, however, can be captured by these models. The group also discussed the utility of more complex, deterministic models which provide greater flexibility to assess a system's response to specific management actions and human impacts. These models, however, require extensive expertise and time for development. Future applications need to be considered strategically and perhaps as a means for deriving parameters that can inform more simple, empirical models to predict triblet conditions and responses more broadly.

Tidal Prisms

An estuary's tidal prism provides a first-order characterization of hydrochemical residence time in an estuary based on the volume of water in an estuarine system between mean high tide and mean low tide (or volume of water leaving an estuary at ebb tide). Estuarine tidal prisms represent the product of the average tidal range and average surface area of an estuary. Comparative empirical studies indicate that tidal exchange, as captured by tidal prism estimates, is related to downstream hydrologic interactions, geomorphology, and residence time. For example, more confined channels tend to have more considerable tidal variation, and thus larger tidal prisms than wide, open estuaries.

Although tidal prism is a powerful tool for evaluating estuarine function, it does not capture the full range of conditions affecting hydrologic exchange along an estuary channel. Explicitly, it does not account for effects of wind, water temperature, water chemistry, and seasonal and short-term weather effects, all of which may be especially crucial to circulation dynamics in the Chesapeake Bay and its nested tributaries.

Flow Return

Like the tidal prism, the flow return index characterizes tidal exchange within an estuary for comparison to other systems. Estimates represent the fraction of embayment water exiting an estuarine system during ebb that returns during the flood tide and ranges from 0 to 1. A low flow return (0) indicates an embayment is maximally flushed by the tide, whereas a high flow return (1) indicates an embayment does not flush. Also, like the tidal prism, however, the flow return ignores or does not explicitly capture the effects of additional mechanisms affecting hydrologic circulation patterns across time and space.

Unstructured-grid Models

Deterministic, numerical models provide more capacity than simple empirical models to explore how changes in riverine and tidal inputs, due to shifting weather patterns, watershed condition, and channel bathymetry, affect estuarine circulation and water quality conditions. For example, Liu and others (2017) used an unstructured-grid application of SCHISM (Semi-implicit Cross-scale Hydroscience Integrated System Model) to evaluate impacts from a bridge structure on estuarine circulation, compared to oceanic influence, in the Lower Bay's James River estuary (Figure 8A). Along the Chester River estuary, in the Upper Bay, SCHISM was applied to evaluate the effects of bathymetry and local catchment discharge on the tidal exchange (see Figure 8B). Comparing the results of these two model applications suggests that bathymetry amplifies effects of local discharge more so than artificial pier structures. Despite the demonstrated utility to compare these model applications, however, it is essential to remember that these models were not developed for cross-system comparisons. A more strategic framework for integrating the results of SCHISM (or other dynamic numeric estuarine circulation models) across multiple systems of the Chesapeake Bay's mainstem could reveal how these nested systems, including triblets, tributaries, and the Bay's main stem, influence circulation patterns across multiple spatial and temporal scales.

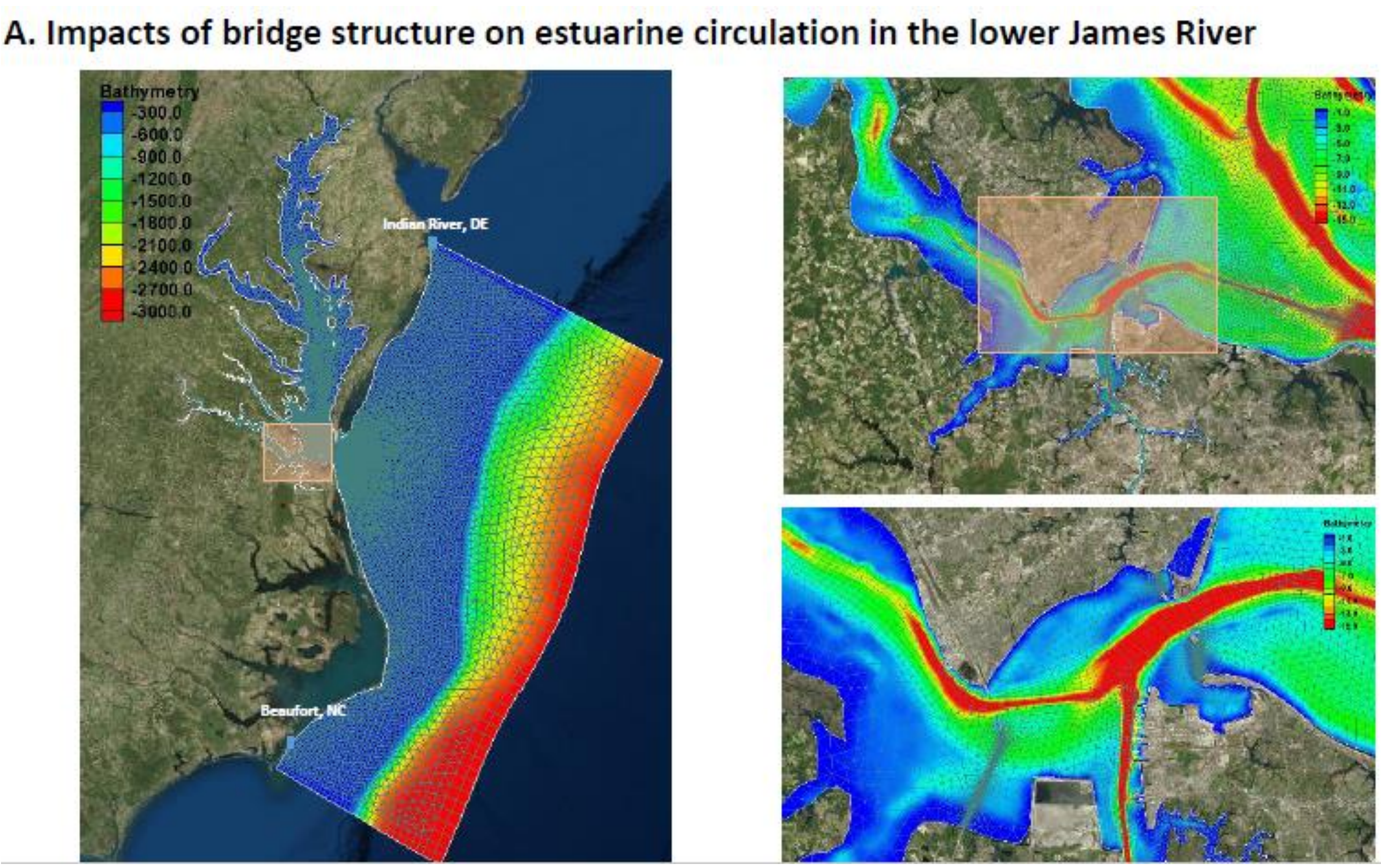

Figure 8. *Examples of unstructured-grid SCHISM applications to Chesapeake Bay tributaries and their triblets. A) Impacts of a bridge structure vs. oceanic influence on the James River; B) Effects of bathymetry and local catchment discharge on the Chester River. From Liu et al., 2017.*

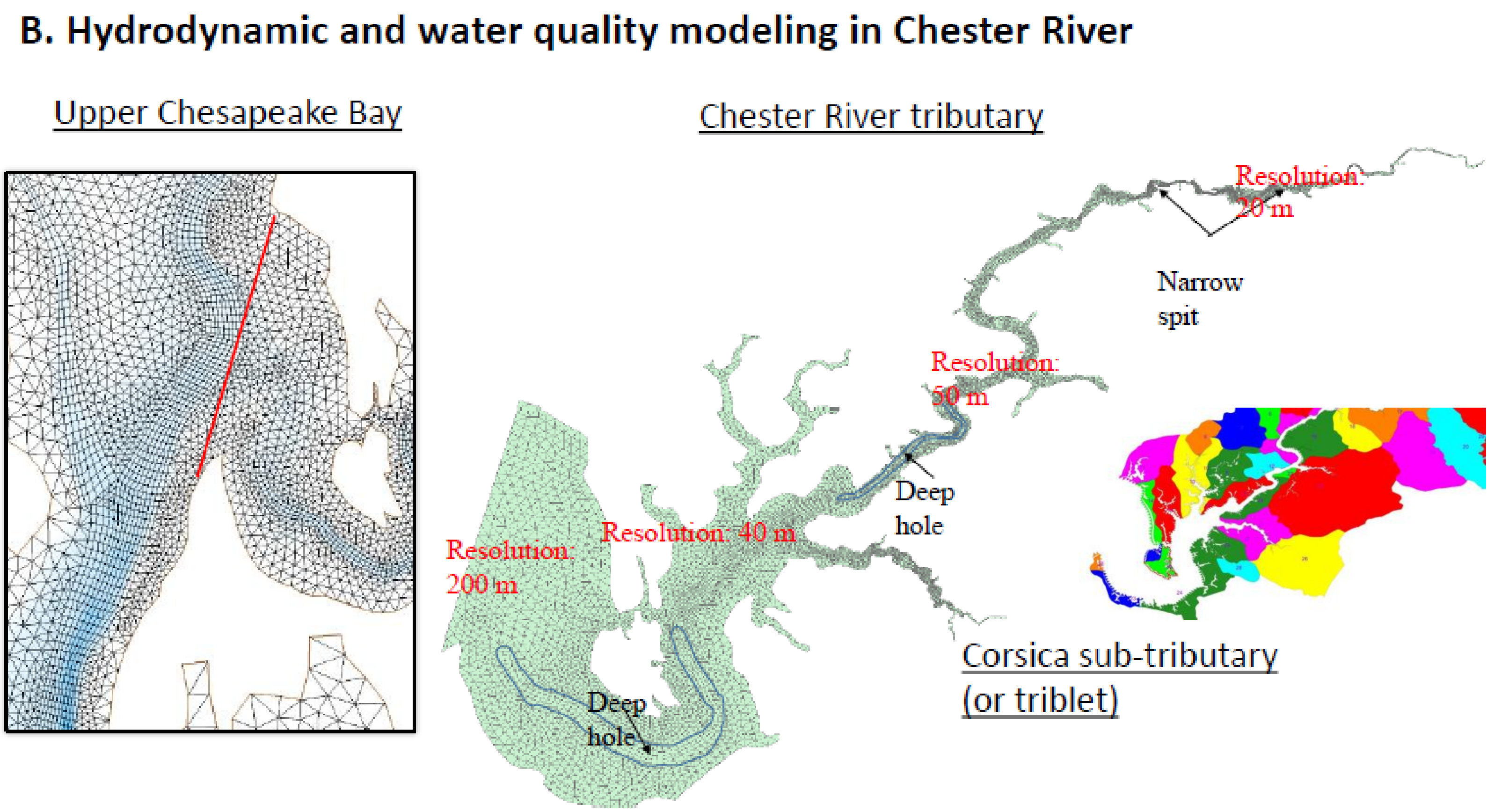

Figure 8 (continued). A) Impacts of a bridge structure vs. oceanic influence on the James River; B) Effects of bathymetry and local catchment discharge on the Chester River. From Liu et al., 2017.

Simple empirical models, however, may not adequately describe or capture controls on triblet and tributary conditions, as well as triblet hydrography. Water quality conditions strongly depend upon short-term, seasonal, and interannual weather patterns. Accordingly, more sophisticated mathematical models, based on trigonometric functions (Ottestad 1984), for example, have additional potential to capture spatiotemporal dynamics within a triblet system. Indeed, there was vigorous discussion regarding the science community's tendency to assume water quality trends are linear, rather than periodic or wavelike. Advanced remote sensing data, such as non-stationary spectral analyses, can provide detailed observations needed to evaluate these signals, and a wavelet-based neural network model could provide a cost-effective modeling approach to address some of the common obstacles to modeling estuarine circulation and water quality conditions (Muller and Muller 2014).

Why modeling triblet response to management strategies remains challenging:

Characterizing triblet function to predict management effects is complicated by variation among and within triblets. Despite the variability, observed parallels among nested systems and systems in different geographies should enable identification of similar zonal patterns (e.g., dissolved oxygen or water clarity) due to similarities in hydrogeomorphic setting and watershed conditions. With this information, managers might have a better understanding of where Bay species of particular concern may have a stronger likelihood of responding to management actions and also a better understanding of relative benefits associated with advanced watershed, shoreline, and coastal management actions. For example, county planners charged with developing Watershed Implementation Plans (WIPs) would like to know whether to focus or concentrate best management practices (BMPs) within highly sensitive or degraded triblet catchments. Alternatively, perhaps the same benefits accrue when BMPs are scattered randomly across a county or tributary watershed. More importantly, county planners and health officials want to know where water quality concerns pose environmental safety risks and how to abate those risks.

Although it is increasingly evident that triblets represent key elements of a tributary system, our understanding of triblet dynamics within the T-zone remains limited. Strategic implementation of more complex models likely is needed to understand how these nested systems respond to human impacts and management actions. Potential management actions include watershed BMP implementation, living shorelines development, modified dredging plans, and submerged aquatic vegetation restoration, among others. Managers need to understand the relative benefits of these practices, where these are most effective, and how much is needed to achieve Bay restoration goals. Further, biophysical models should provide information to help evaluate costs and benefits based on stakeholder concerns.

Given the uncertainty, multiple model comparisons may have the best potential to advance our understanding of triblet–tributary–Bay circulation and biogeochemistry most efficiently. Ideally, the model set will include different hypotheses regarding system drivers.

The appropriate spatial scale or the size by which to define a triblet also presents a challenge. One idea that emerged is to develop an estuary classification system similar to the stream-order framework used by fluvial geomorphologists but in reverse order: Continental shelf as zero-order, Chesapeake Bay would be first-order; major tributaries would assume second-order classification, and triblets would represent third-order tributaries. Similar to stream order, the classification would provide some indication of waterway's size and potential influence on the overarching estuarine system.

Why the CBP should recognize triblets as critical landscape elements

Triblets and the T-zone represent a critical but overlooked set of landscape elements where freshwater-tidal interaction affect a range of biogeochemical processes critical to estuarine health. There is limited research on this critical transition zone, which is reflected in the CBP's regulatory model structure. The prescribed TMDL "nutrient diet" is based on how non-tidal discharge through major tributaries affects the main stem's condition. Intervening land areas are modeled as providing direct discharge to the Bay, based on an extrapolation of modeled data from non-tidal segments. Coastal wetlands are included as part of the estuarine model and are assumed to sequester nutrients and sediments uniformly. In contrast to this simple scheme, this workshop highlighted the important but complex and understudied role of the transition zone between non-tidal watershed sub-basins and open water estuaries. Triblets act as natural bioreactors that strongly influence chemical fate and transport and habitat quality for living resources. Perhaps most importantly, triblets are highly visible and valuable to stakeholders and are also where the highest density of human impacts tends to occur. Land and water management in the T-zone is essential to mitigating human impacts to the Chesapeake Bay and managing effects of sea-level rise.

Figure 9: CBP6 land-river segment modeling elements. Green segments are identified as, "Draining to Tidal Water – No River Simulation," and likely represent a large portion of the terrestrial-estuarine transition zone deemed critically important to Bay resources of concern.

Triblet corridors function as bioreactors to regulate exchanges between land and waters

Triblets represent tidally-coupled, natural biogeochemical reactors that can act as direct conduits of pollutant loads to estuarine waters, but also where steep hydrochemical gradients sustain complex bigeochemical processes which influence the fate and transport of nutrients and other contaminants of concern. These complex interactions impose strong influence on shallow water and near-shore habitat. Like all ecosystems, each triblet has unique spatiotemporal patterns of flow, hydrographical conditions (temperature, salinity, turbidity, and water depth) and hydrochemical gradients, reflective of its hydrogeomorphic setting. Along the triblet length, the extent of estuarine mixing controls sedimentation, nutrient availability, dissolved organic matter dynamics, and biological activity within the water column. These physio-chemical conditions influence the biological community, including the establishment and maintenance of phytoplankton, benthic algae, submerged aquatic vegetation, and wetland macrophytes. Interactions among various water sources create unique conditions that strongly influence habitat and water quality conditions. In the T-zone, we can expect even stronger biogeochemical activity affecting nutrient availability and turbidity, due to the mixing between fresh- and oceanic waters.

Sediment dynamics along a triblet's longitudinal axis provide a powerful example highlighting the importance of landscape elements as transitional zones between terrestrial and estuarine systems. A complex set of linked biogeochemical interactions occurs along triblet corridors from above the micro-tidal zones to estuarine mouths (Ensign and Noe 2018). Near the micro-tidal zone, river stage approaches base level and channel flow velocities slow significantly. As a result, deposition rates of carbon- and nitrogen-rich sedimentation rates increase significantly. The rate of sedimentation is significant enough to limit downstream sediment supply to downstream areas and potentially limit capacity for coastal marshes to accrete as sea-level rise occurs; thus, this phenomenon is referred to as a sediment shadow (Figures 10, 11). At the downstream areas of the triblet and T-zone, sedimentation rates also are higher in oligohaline marshes, in part due to sediment supply by the main stem of the Bay and shoreline redeposition (Colman et al. 1992). Limited sediment supply reduces the capacity for tidal marsh development to occur with sea-level rise (Ahnert 1960).

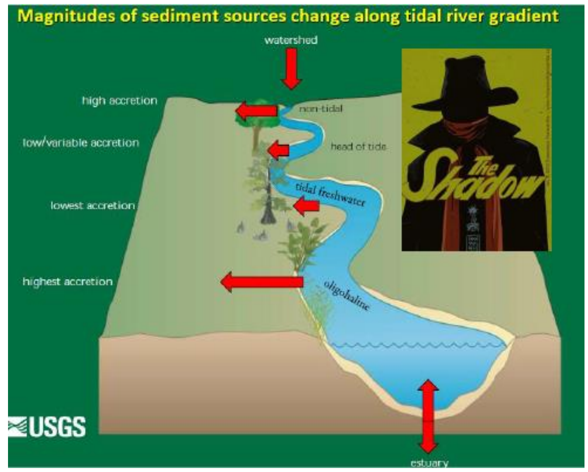

Figure 10. Conceptual model of triblet sediment dynamics, highlighting two zones of significant accumulation: upstream, where the river gradient approaches base level and enhanced sedimentation creates a sediment shadow; and downstream, where watershed discharge and estuarine processes more directly interact (Noe 2018).

The observed variation in triblet sediment dynamics can help inform the extent of the T-zone, which ties closely to regional physiography (Figure 12). On the Chesapeake Bay's western shore, the micro-tidal zone extends from the Piedmont fall line to beyond the mouth of the mainstem's tributary. Due to the steep relief associated with the fall line, the upgradient extent of the T-zone is not likely to shift as sea-level rise occurs. In contrast, on the Eastern Shore, deep unconsolidated sediments do not exert the same influence on the migration of micro-tidal zone as do the bedrock outcrops that form the Western Shore's fall line. The inland extent of the T-zone depends on sea level and is sensitive to tidal anomalies as well as changes in channel morphometry.

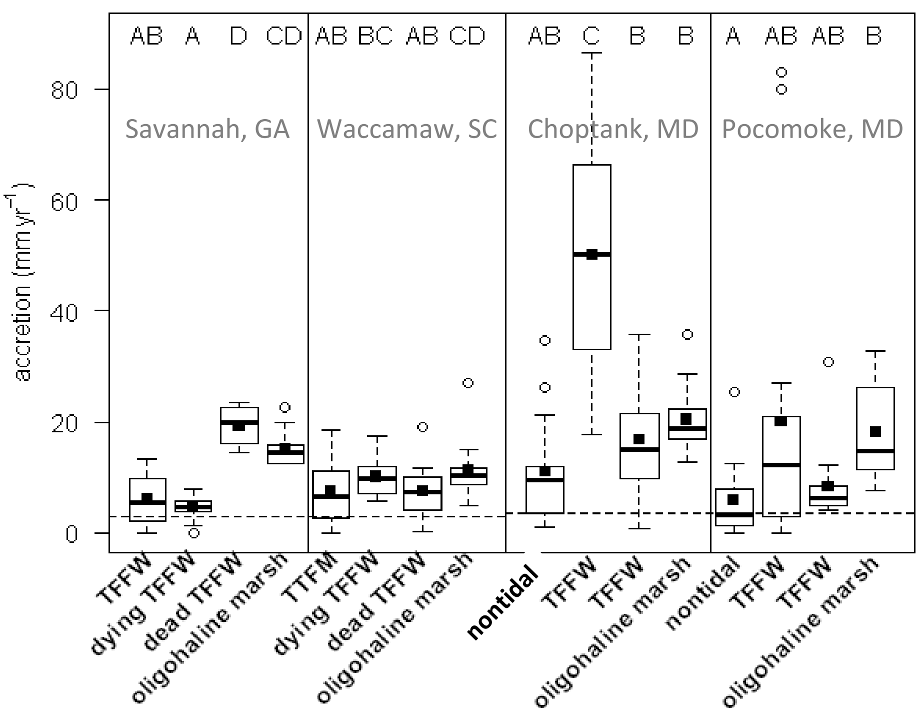

Figure 11. Observed sediment accumulation along four Coastal Plain triblet systems, highlighting two zones of significant accumulation: Upstream, tidal forested freshwater (TFFW) zones where the river gradient approaches base level, and downstream oligohaline marshes where watershed discharge and estuarine processes more directly interact (Noe 2018). Sediment accumulation is lower at intermediate TFFW zones where dying vegetation indicates effects of sea level rise and longer flooding durations.

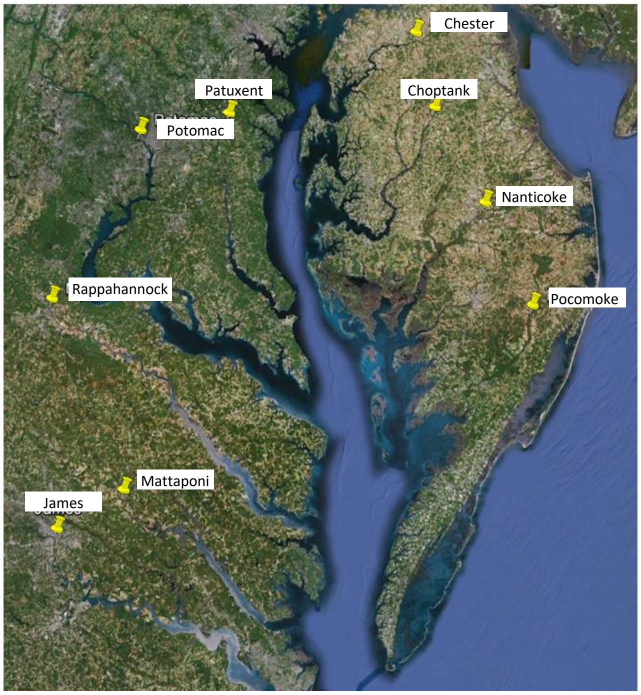

Figure 12. *Upstream sediment deposition zones identified by yellow pins can provide potential basis for identifying up-gradient extent of the terrestrial-estuarine transition zone (T-zone) (from Ensign and Noe 2018).*

Nutrient exchange ties closely to sediment dynamics. At the upstream limits of the T-zone, coarse sands and silts primarily are deposited while clay particles and particulate organic matter remain suspended until settling in open, standing water in the mid- to lower estuary. These fine-textured clay particles are highly reactive to which nutrients, dissolved organic carbon, and contaminants of concern readily adsorb. When exposed to low-oxygen environments, microbial activity can release sorbed constituents, including phosphorus and other redox-sensitive toxins. Reduced, low oxygen conditions tend to occur where turnover with oxygenated waters or exposure to the atmosphere is limited due to poor hydrologic circulation, for example in bottom waters of a stratified system or deep pockets of an estuary. Reduced conditions are likely to prevail, especially during warm, summer conditions when wind events occur less frequently. Nitrogen dynamics also vary along the longitudinal axis of T-zone triblets and laterally across triblet corridor, including adjacent floodplains, in response to redox state, pH, and salinity gradients. Under the most reduced conditions, N can remain in its most bio-available form, as ammonium (NH_4^+). At the suboxic interface between oxygenated and reduced waters, conversion rates from bio-available N forms to inert N_2 gas via nitrification and denitrification are highest. Measured sediment N release rates (NH_4^+, NO_3^-, and N_2) are exceptionally high in downstream triblet sediments compared to marsh sediments, and strongly affected by triblet conditions, including temperature and turbidity due to (re)suspended sediments (Figure 13).

Excess nutrients shift food web dynamics, for example, by enhancing phytoplankton production or via rapid uptake of elevated nitrogen, creating ideal conditions for toxic nitrogen-fixing cyanobacteria.

Similar to the mainstem, the estuarine turbidity maximum (ETM) presents a potentially significant control within the T-zone, especially across deeper triblets. Steep hydrochemical gradients form where terrestrial freshwater and saltwater sources interface and enhance microbial processes critical to food web dynamics. The ETM migrates longitudinally along a channel in response to currents, and both short- and long-term weather patterns.

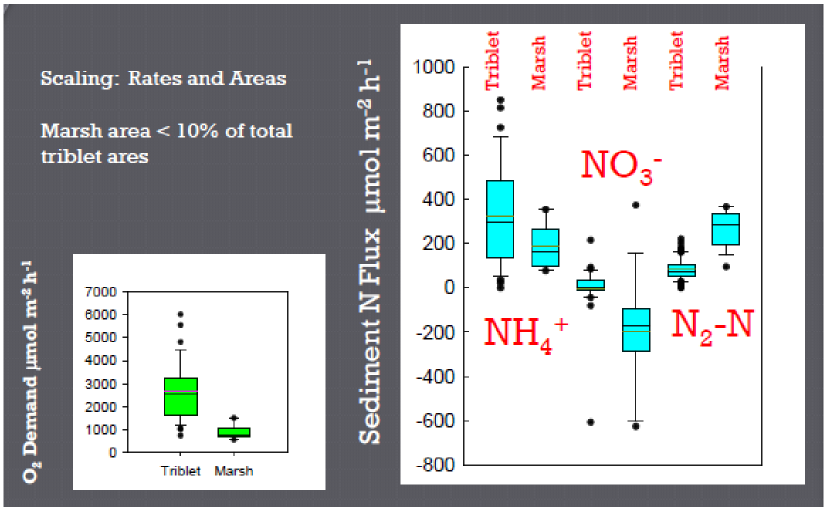

Figure 13. *Comparison of N fluxes among triblets and coastal marshes in the Chesapeake Bay's Corsica River (from Cornwell, Palinkas and Boynton).*

Triblet corridors provide critical habitat

Triblets include a disproportionate area of the Chesapeake Bay's shallow waters. Brackish waters historically provided critical habitat for high priority species including blue crabs and submerged aquatic vegetation, oyster reefs, and other benthic fauna (Ihde et al. 2015). Triblets are used as spawning and nursery areas when aquatic species are most sensitive to exposure and effects on development, reproduction, and immune response capabilities. Further inland, tidal freshwater wetlands provide critical spawning habitat for key commercial fisheries (e.g., striped bass, and white and yellow perch), nesting and migratory waterfowl (e.g., black duck, redheads, and canvasback), and freshwater mussels which provide an essential food source to species of concern. Intervening areas, where the water table remains near the land surface to preclude establishment of woody species, provide critical habitat to rare and endangered species including the secretive black rail and salt marsh sparrow.

In addition to providing critical habitat for species of concern, degraded triblet corridors can be especially susceptible to the establishment of harmful and invasive species. For example, cyanobacteria blooms often occur in shallow, tidal freshwaters with low pH buffering capacity due to watershed discharge. Harmful algal blooms (e.g., *Cochlodinium polykrikoides* and *Alexandrium monilatum*) often initiate as triblet 'hotspots,' followed by "incubation" and transport to the larger tributary system. Larger freshets following intense storms have allowed invasive species including blue and flathead catfish (*Ictalurus furcatus* and *Pylodictis olivaris*), Northern snakehead (*Channa argus*) and other invasive species to expand their range throughout the Chesapeake Bay tributaries (Ihde et al. 2015).

Triblet corridors are highly visible and valuable to stakeholders

The Chesapeake Bay is revered for its commercial and recreational fisheries as well as its many water sport opportunities. Development intensities and property values continue to increase along triblet corridors. These smaller waterways provide access to Bay resources but also to see the effects of human impacts more closely tied to their activities. Therefore, the triblet concept has strong potential to provide a powerful management framework that will effectively engage the public. Restoration projects developed in close collaboration with residents often achieve strong buy-in and commitment to protecting local waters. In contrast, CBP's focus on the mainstem has enabled diffusion of responsibility among stakeholders and even challenged the credibility of CBP management recommendations because stakeholders cannot relate their observations and experiences to CBP-issued guidance.

Triblet conditions are more responsive to watershed condition and management

Aquatic resources in smaller triblets are more vulnerable to human impacts. Advanced technology to monitor habitat and water quality conditions more frequently and with more detailed resolution show wide variation in triblet condition. Some triblets are so degraded due to poor catchment management that these small systems function as point sources of pollution to mainstem tributaries (Muller and Muller 2014). Imposing excess nutrient and pollutant loads, increased turbidity, and elevated temperatures reduce the viability of eggs, larval, and juvenile fish. While triblets are more prone to impairment, more immediate responses to advanced watershed management also are likely in these nested micro-systems.

Triblets: A powerful framework for studying and managing land-water interactions in the terrestrial–estuarine transition zone

There is a clear need to advance watershed and estuarine research that is relevant to local planners and restoration managers; that is to provide decision-makers with reliable information that bolsters confidence in their investments toward sustaining adequate, clean waters for recreational and commercial needs. Triblets and their T-zone emerge as critically important landscape elements because of their visibility and sensitivity to human activities. The close relationship between triblet condition and historical watershed management presents a powerful opportunity to better understand the role of surface water corridors within the T-zone and the benefits of advanced watershed management. Further, the size and number of triblet systems, as well as their distinctness from the mainstem systems, provide a compelling basis to advance our understanding of land-water linkages, especially if an intentional and strategic combination of modeling and field studies are applied. The definition of a triblet may evolve, but the current concept undoubtedly can advance watershed, shoreline, and Bay management in the face of landscape and climate change.

Similarly scaled catchments throughout the entire watershed may bring much-needed attention to non-tidal first-order streams, as these provide critical linkages between terrestrial and aquatic ecosystems and a compelling framework for promoting stakeholder engagement.

Recommendations for Promoting Science-Based Triblet Management

- **Establish objectives and define targets for advanced triblet management.** A range of stakeholder concerns beyond water quality influence watershed management allocations for restoring the Bay. Stakeholder concerns, including their understanding of system dynamics, must be incorporated when defining and evaluating management alternatives (e.g., Table 1). Measurable targets should reflect these concerns (e.g., Table 2). A comprehensive approach to stakeholder engagement could advance CBP goals more effectively.
- **Identify high priority triblet catchments** where comprehensive management can provide maximum, measurable benefits to water quality, habitat, and living resources. Ideally, this modeled information would include high-resolution maps of triblets and triblet condition, along with expected Bay system response(s) to management actions.
- **Select integrated practices in strategic location(s) to restore processes in addition to habitat**. Improving triblet condition requires a comprehensive suite of innovative watershed, shoreline, and in-channel practices that can reduce artificial flow constrictions and restore natural environmental flows. For example, on the West Coast, the successful Napa River restoration required raising and relocating bridges, realigning traffic infrastructure, and creating channel by-passes at critical locations, in addition to traditional practices such as wetland restoration and improved land use management.

TABLE 1: Potential concerns that ultimately may influence resource allocations to Bay restoration efforts.

CBP Concerns:
- Total Nitrogen (TN)
- Total Phosphorus (TP)
- Total Suspended Sediments (TSS)

Potential Stakeholder Concerns:
- Swimmable waters
- Fish consumption safety and risk
- Adequate recreational fish populations
- Shoreline erosion
- Recreational accessibility
- Boating accessibility
- Sedimentation
- Flooding
- Economic viability for watermen and farmers
- Maintenance requirements
- Cost

TABLE 2: Potential indicators to address stakeholder concerns.

Water Quality Conditions Total Maximum Daily Loads:
- Total Nitrogen, Total Phosphorus (lbs/yr)
- Total Suspended Sediments (tons/yr)

Macrobiota Indicators:
- Coastal marsh habitat (m^2)
- Submerged Aquatic Vegetation (m^2 or % of triblet bed)
- Population of marine resources of concern, including oysters (reef area), blue crabs, striped bass (number/area)

Microbiota Indicators:
- Harmful algal toxins (ug/100 g shellfish)
- Harmful algae (cells/mL)
- Fecal bacteria (colonies/100 mL water sample)
- Other harmful bacteria (colonies/100 mL water sample)
- Zooplankton composition (%)

Other:
- Cost ($)
- Crop yield (e.g., bushels/year)
- Commercial fisheries catch (e.g., catch/unit effort)
- Field erosion (tons/acre/yr)

Chemicals of Emerging Concern:
- Pharmaceuticals (ug/L)
- Human & livestock hormones (ug/L)
- Pesticides (ug/L)
- Optical brighteners (ug/L)
- UV blockers, antimicrobials (ug/L)
- Other Personal Care Products (ug/L)
- Microplastics (g/km2)

Physio-Chemical Conditions:
- Anoxic volume (m3)
- Elevated temperature (days per year greater > 25°C)
- ETM zone (triblet's longitudinal position)
- Turbidity (Secchi depth; NTUs)
- Shoreline erosion and retreat (m/yr)
- Sedimentation rate (mm/yr)
- Flood frequency (frequency, m depth)
- Shoreline armoring (% of shoreline)
- Shoreline armoring rates (m/yr)

- **Mitigate the most significant impacts on advancing CBP goals.** Key impacts affecting coastal resources include the combination of excessive fertilizer applications (past and present) together with extensive artificial hydrologic networks, which shunts runoff from development and impervious surfaces, high-intensity agriculture, and concentrated livestock operations directly to regional waters. Poor T-zone management, including loss of natural filters (e.g., wetlands, SAV beds, oyster reefs) and hardened shorelines also affect shallow waters throughout the T-zone, including triblets. Finally, channelization of dredging along triblets and tributaries significantly affects water quality conditions through effects on lateral transfer of nutrients and sediment and estuarine circulation. Advancing restoration of the Bay's shallow waters requires a better understanding of the relative impacts and interactions among these human impacts (and potential management strategies) throughout the T-zone.

- **Implement comprehensive management plans ("Living River Strategy") to restore natural processes within a complete system, including catchment shorelines and open channel practices.** For example, coastal restorations should allow for a full range of natural habitats and transition zones along natural hydrologic gradients, including submerged aquatic vegetation and living shorelines, salt marsh, and transition zones to up-gradient freshwater wetlands along triblets. This comprehensive approach will allow natural processes to expand, including alluvial fan deposition, stream delta deposition, tidal overbank deposition, wave deposition, and coastal community migration. Similarly, floodplain restorations should address channel modifications, lateral ditches, as well as artificial levees that have altered the hydroperiod, rather than focusing on a single element of hydrologic alterations affecting floodplain function.

- **Advance research to develop innovative management strategies**. As we continue to refine our understanding of how human activities influence biogeochemical processes along triblet corridors and throughout the T-zone, new ideas and insights will emerge regarding how best to manage these systems and mitigate adverse impacts. There is an urgent need to invest in developing new technologies, accordingly, as well to investigate best designs and implementations of currently prescribed management practices.

Recommended Science Technical Advisory Needs and Research

Defining Objectives and Restoration Targets:

- **Revisit sediment management objectives** to reflect importance or significance of deposition patterns, both with respect to where and which (texture) sediments are delivered throughout the nested Bay system.
- **Explicitly address catchment water storage, water temperature, and toxic pathogens** as critical concerns in Chesapeake Bay watershed management.

Identifying Management Strategies:

- **Investigate novel approaches to shoreline, near-shore, and open water/channel management and optimal designs affecting triblet and estuarine conditions**, including the establishment of living shorelines, oyster reefs, and submerged aquatic vegetation; and boating guidelines to address concerns associated with sediment resuspension and altered estuarine circulation patterns.
- **Investigate management opportunities/strategies to reduce the risk of bacteria and algae blooms**, possibly including watershed, shoreline, and estuarine channel management. For example, prioritize practices that mitigate temperature stress and limit resuspension of fines, organic matter, and resting stages of planktonic organisms.

Evaluating and Informing Management Efforts:

- **Identify dominant biophysical processes affecting triblet condition, highlighting where/how human activities and management may affect those processes most significantly.**
    - Recognize and investigate alternative hypotheses (competing conceptual models)
    - Characterize and evaluate the uncertainty of boundary condition controls (e.g., the relative importance of Bay vs. mainstem vs. triblet inflows/outflows)
- **Investigate the effects of emerging contaminants and contaminants of concern on nutrient cycling and food web structures, as well as on both recreational and commercial concerns**.

- **Characterize (map) variability and condition among triblet systems based on biophysical processes and identify those that are sensitive to human interventions, at a spatial-temporal scale relevant to resource managers.**
    - Develop high-resolution models to evaluate how triblet watershed management, human infrastructure, and alterations of tributary basins (including triblets) affect watershed-estuarine interactions; evaluate potential sensitivities to human activities and climate change.
    - Identify tributary systems where more detailed numerical models can provide critical insights regarding interactions between triblets and tributaries and their response to watershed management and climate change.
    - Explore the utility of artificial neural network models to extrapolate long-term prediction based on more complicated hydrodynamic and biogeochemical models.
    - Evaluate temporal trends reflective of shifting seasonal, weather, and climate conditions.
    - Investigate the utility of spectral characterizations and wavelet analyses to improve the spatial and temporal resolution of understanding triblet systems and dynamics (e.g., processes affected by extreme weather events).

Advancing Implementation:

- **Investigate social and economic concerns presenting barriers and opportunities to stakeholder engagement across the T-zone and triblet systems.**

Measuring Outcomes:

- **Leverage existing water quality monitoring data to inform triblet model development but also review triblet model predictions to guide future monitoring efforts.** The smaller sizes together with the sheer number (the 1000's) of triblets present novel and exciting opportunities to explore how triblet condition reflects physio-chemical gradients affected by natural and anthropogenic drivers (i.e., to evaluate competing conceptual models).

Recommendations specific to the CBP Modeling Framework

In addition to management and research recommendations, the workshop panel identified opportunities to advance the Chesapeake Bay Program's management framework:

Refine the CBP model segmentation strategy to reflect the importance of triblet catchments. Phase 6 land-river segments in coastal areas are mostly unchanged, e.g., are similar in scale to USGS HUC12/14 segmentation. Most segments include multiple triblets. This approach may be adequate to decision-making if triblets within a segment function similarly and have comparable impacts from human activities. Given the variability in triblet form and function, however, this *status quo* approach needs to be evaluated carefully. Further, guidance with how to apply or use model predictions in a decision context focused on triblet function and health is needed.

Focus CBP modeling and management efforts on the terrestrial-estuarine transition zone (in addition to non-tidal and estuarine focus areas)**.** This workshop highlighted the limitations of the current model, which does not explicitly model the T-zone and its triblets. Evidence from this workshop and recent literature (e.g., Xenopoulos et al. 2017; Collins et al. 2015), highlight the importance of the transition zones, both in terms of functioning as bioreactors that potentially moderate or alter impacts from upland catchments and as critical habitat for coastal resources of concern (e.g., oysters and crabs, nursery habitat for fisheries, and river/marine recreation and tourism).

The CBP6 modeling strategy parallels the development of land-water research, which historically siloed disciplines to focus on watershed hydrology in non-tidal segments and open water estuarine circulation: Wetlands provide a powerful example of the limitations imposed by this modeling framework. In the current model structure, wetlands are represented either as non-tidal or coastal landscape units that sequester nutrients and sediment. The discussion summarized herein, however, highlighted the dynamic processes and variability of wetland function along triblet corridors, which strongly depends on triblet morphology and condition. This "isolated" modeling strategy minimizes the vital role of triblets and triblet wetlands as critical transition zones affecting temperature regimes, salinity gradients, redox conditions, C dynamics, nutrient availability, food web structure, and living resource quality.

Conclusions

Is the triblet concept helpful in investigating and predicting the Bay's response to watershed and coastal management, sea-level rise, and climate change?

The workshop panel unanimously concluded that, yes, ABSOLUTELY the triblet concept is helpful and essential to advancing Bay management and research. Triblets significantly influence shallow water conditions and habitat quality for highly valued living resources. Triblet catchments present tractable study units to advance our understanding of how historical and advanced resource management affects living resources, now and in the face of climate change: these are small enough to link measured conditions to human activity and numerous enough to provide a robust basis for empirical studies. Further, triblets likely represent a spatial scale at which we can strategically implement practices and expect to observe measurable outcomes and effects on ecosystem processes. Most importantly, triblets are relevant and highly valued by local stakeholders. Already, the triblet concept has proved a strategic scale for engaging stakeholders with potentially conflicting concerns and developing collaborative solutions.

In short, substantial evidence exists to recommend triblets and triblet catchments as critical opportunities for advancing Bay restoration goals and prioritizing restoration strategies.

- Triblets and triblet catchments represent a meaningful spatial scale for watershed planning.
- Triblets are highly valued by stakeholders.
- Triblets represent direct linkages between upland watersheds and Bay resources of concern.
- Variation in triblet conditions indicates sensitivity to human activities, including watershed and shoreline management, channel dredging, and substrate agitation.

The T-zone concept also emerged as a powerful framework for understanding linkages between terrestrial and estuarine systems. Triblets, including open water channels and adjacent floodplain corridors, function both as conduits and bioreactors, and thus represent a critically important element of the T-zone. Human activities continue to concentrate within the T-zone, and thus present both critical threats and opportunities to advancing the Bay's restoration.

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Appendix A: Workshop Agenda (with links to presentations here)

Revisiting Coastal Land-Water Interactions: The Triblet Connection

A Scientific and Technical Advisory Committee (STAC) Workshop

Hood College, Frederick, MD
May 23 - 24, 2018

Overview: Small tributaries, with watershed areas typically less than 5,000 ha (20 square miles) and cross-sectional widths less than 100m wide (or "triblets") but larger than coastal wetland tidal creeks, can vary widely in water quality conditions and in their effects on coastal photic zone resources (Morse et al. 2013). For example, observed mean dissolved oxygen concentrations ranged from 0 to 10 mg/L among ten triblets of the South River (Muller and Muller, 2014) and similar systems investigated outside of the Chesapeake Bay system (Keppler et al., 2015; Lerberg et al., 2000). Forcing drivers, however, remain uncertain. Studies of the Chesapeake Bay mainstem and its tributaries (e.g., Testa et al 2017, Linker et al, in prep) suggest estuarine gradients in these nested systems are strongly influenced by similar drivers, including basin morphometry, water residence time, and watershed condition; thus, the same drivers may influence interactions between triblets and their tributaries. Developing a conceptual model (or set of alternative models) to characterize triblet-tributary interactions based on larger-scaled studies could be invaluable to identifying which triblets in impose a disproportionate influence upon Bay health and to predicting where, when, and how Bay health will respond to land and water management.

Overarching Discussion Questions:

- What would a conceptual triblet-tributary model look like?
- Can such a conceptual triblet model inform comprehensive watershed and coastal management? Does watershed or coastal management based on triblet condition present disproportionate opportunities to advance Chesapeake Bay Program goals (e.g., SAV, blue crabs, oysters restoration), perhaps because of shoreline location, circulation patterns, watershed condition, and/or coastal management operations? How can we predict which triblet systems have a disproportionate influence upon Bay resources of concern in different sub-estuaries along the mainstem of the Bay?
- How does coastal management and watershed condition affect triblet-tributary interactions? How might triblet-tributary interactions change due to shifting climate regimes? How might emerging contaminants of concern or other human influences affect triblet condition and influence on Bay resources?

Workshop Objectives:

- Develop a synthesis of current estuarine science to refine our model(s) of land-water linkages, specifically to evaluate mixing zones and patterns (e.g., salinity, temperature, nutrient concentrations, chlorophyll and other pigments, DO) in small tributaries ("triblets") affecting key Bay resources of concern and influenced by a range of management practices.
- Develop a conceptual model (or set of models) that can be used to identify sub-watershed areas that have a disproportionate impact on biotic conditions of concern
- Identify critical knowledge gaps limiting our ability to provide guidance to restoration managers regarding drivers affecting estuarine circulation, habitat condition, and Bay resources of concern.

Day 1 – Wednesday, May 23

9:30 am **Welcome, Overview of Workshop Goals, Introductions -** *Kathy Boomer (TNC)*

9:45 am **DAY 1 PLENARY** - *Dr. Peter Goodwin (UMCES)* Historical/continental/global overview of our understanding of the linkages among shallow bay resources, local circulation patterns, and watershed management. How can current research advance these paradigms?

10:30 am **Q&A**

10:45 am **BREAK (15 mins)**

Session I: Triblet-Tributary Linkages Discovered Within and Outside the Chesapeake Bay Watershed

11:00 am **Session Overview/Introduction** *(Moderator - Diana Muller)*

Key Questions:

- Which biotic conditions show greatest susceptibility to local circulation and water quality conditions affected by human activities?
- Are there patterns in health, condition, and/or distribution that yield insights into better understanding of land-water connections?
- Evidence of effective watershed or coastal management practices?

11:05 am **Triblet Characteristics and Responses** - *Kevin Sellner (Hood) et al.*

11:25 am **Terrestrial Drivers of Coastal Plain Stream Water Quality in North Carolina** - *Michael Mallin (UNC Wilmington)*

11:45 am **Coastal Development and Tidal Creek Environmental Quality in the Southeastern US** - *Denise Sanger (SCDNR)*

12:05 pm **The Spectral Signature of Water Quality Stressors in Chesapeake Bay Triblets -** *Andrew Muller (USNA)*

12:25 pm **Q&A; Discussion**

12:35 pm **LUNCH**

Session II: Advances in Understanding Sub-Estuarine Circulation Dynamics

1:30 pm **Session Overview/Introduction** *(Moderator - Kathy Boomer and Bruce Vogt)*

Key Questions:

- What is the relative influence of triblets vs major tributary main stem vs Chesapeake Bay main stem in affecting sub-estuarine circulation patterns?
- How might triblet patterns of salinity, temperature, turbidity, and other water quality/biotic indicators vary in relation to freshwater inputs and circulation patterns? And in relation to shoreline position?
- How might coastal management influence triblet-subestruarine interactions?
- How might shifting weather patterns influence triblet-subestuarine interactions?

1:35 pm **A segmented tidal prism flushing model for triblets -** *Larry Sanford (UMCES)*

1:55 pm **The Trouble with Triblets** - *Lora Harris (UMCES)*

2:15 pm *Harry Wang (VIMS)*

2:35 pm **Q&A; Discussion**

2:50 pm **BREAK (25 mins)**

Session III: Advances in Understanding Watershed Effects on Sub-Estuarine Conditions

3:15 pm **Session Overview/Introduction** *(Moderator - Andrew Muller)*
Key Questions:

- Spatial-temporal response of hydro-biogeochemical gradients to watershed discharge, storm events, and/or other external drivers in shallow (< 6 m) estuarine environments
- Evidence of effective watershed or coastal management practices?

3:20 pm **The Triblet Connection: Nodal Point Pollutant Sources in the South and Severn River Estuaries** - *Diana Muller (Maritimas)*

3:40 pm **The subestuary concept: A powerful paradigm for land-water interactions in estuaries -** *Tom Jordan and Don Weller (SERC)*

4:00 pm **Freshwater-Tidal Gradients: Eco-geomorphology linkages to watershed-estuarine dynamics -** *Kathy Boomer (TNC), Greg Noe (USGS) and Scott Ensign (Stroud Center)*

4:20 pm **Q&A; Discussion**

4:50 pm **Closing Remarks** *(Kevin Sellner)***; Recess**

5:00 pm **Social Hour hosted by TNC**

Day 2 – Thursday, May 24

8:30 am **Call to Session** - *Diana Muller (Maritimas)*

8:40 am **DAY 2 PLENARY -** *Dr. Jeremy Testa (UMCES)* Recap of Day 1 and connecting to Day 2 discussions: Linking biogeochemical trends across spatio-temporal scales in estuarine environments.

9:20 am **Q&A, Group Discussion, and Shared Reflections**

9:45 am **BREAK (15 mins)**

Session IV: Other Factors Affecting Triblet Condition that Could (at worst) Undermine or (at best) Inform TMDL Management

10:00 am **Session Overview/Introduction** *(Moderator - Kevin Sellner)*

10:05 am **How might Chesapeake Bay Triblets respond to climate change?** - *Ray Najjar (PSU)*

10:25 am **Sustainable Shorescapes: Reconnecting Land and Water** - *Donna Bilkovic (VIMS)*

10:45 am **Organic matter processing in shallow water tributaries – environmental controls** - *Jeff Cornwell (UMCES) and Kathy Brohawn (MDE)*

11:05 am **Stressors of emerging (increasing) concern potentially affecting processes and living resources** - *Vicki Blazer, USGS Chelsea Rochman (U. Toronto), Andrew Heyes (UMCES), and Fred Pickney (USFWS)*

11:25 am Natural events, including Vibrio and HAB's - *Margaret Muholland (ODU), Kevin Sellner (Hood), and John Jacobs (NOAA)*

11:45 pm **Considerations of the Human Dimensions of TMDL Management** - *Liz Van Dolah and Michael Paolisso (UMD) and Lisa Wainger (UMCES)*

12:05 pm **Q&A; Discussion**

12:15 pm **LUNCH**

1:00 pm **Group Discussion - Tying the Pieces Together to Advance Bay Restoration Goals**
Facilitators - *Lisa Wainger (UMCES); Lewis Linker (CBP)*

Potential Discussion Questions:

i. Key take-aways? New insights? Updated conceptual model(s)?
ii. Refining our conceptual model(s): What are main drivers of triblet health, variation in triblet health, and relative influence of different triblets on sub-estuarine health?
iii. Based on workshop findings, can we provide more specific guidance regarding where and how to advance Bay restoration goals? Do triblets and associated catchments provide a more compelling basis to target watershed implementation plans? Can a combination of advanced watershed and coastal management in targeted triblets provide disproportionate benefits to restoring Bay health?
iv. Implications to aquaculture, coastal management, or watershed management?
v. (How) should management recommendations reflect expected climate impacts?
vi. Are there key research/knowledge gaps regarding the role of triblets that limit our capacity to advance Bay goals and which should receive priority funding? How and where should we monitor triblet function? Is there a role for citizen science?

1:45 pm **Wrap-Up: Summary Findings and Overview of Next Steps** *(Kevin Sellner; Kathy Boomer)*

2:00 pm **ADJOURN**

Workshop Products: The final report will summarize workshop findings, including a set of conceptual models that can be used to identify sub-watershed areas that have a disproportionate impact on biotic conditions of concern, and outline important research gaps and opportunities.

Steering Committee: *K. Boomer (STAC/TNC), K. Sellner (Hood), M. Friedrichs (VIMS), A. Muller (USNA), D. Muller (Chesapeake BaySavers), W. Boynton (UMCES), D. Ferrier (Hood), R. Dixon (STAC/CRC)*

Workshop Webpage: http://www.chesapeake.org/stac/workshop.php?activity_id=287

Literature Cited: **Keppler, C.J., D.C. Bergquist, L.M. Brock, J. Felber, and D.I. Greenfield, 2015**. A Spatial Assessment of Baseline Nutrient and Water Quality Values in the Ashepoo-Combahee-Edisto (ACE) Basin, South Carolina, USA. Marine Pollution Bulletin 99:332–337. **Lerberg, S.B., A.F. Holland, and D.M. Sanger, 2000**. Responses of Tidal Creek Macrobenthic Communities to the Effects of Watershed Development. Estuaries 23:838–853. **Morse, R.E., M.R. Mulholland, W.S. Hunley, S. Fentress, M. Wiggins, and J.L. Blanco-Garcia, 2013**. Controls on the Initiation and Development of Blooms of the Dinoflagellate Cochlodinium Polykrikoides Margalef in Lower Chesapeake Bay and Its Tributaries. Harmful Algae 28:71–82. **Muller, A. and D. Muller, 2014**. Analysis of Nodal Point Pollution, Variability, and Sustainability in Mesohaline Tidal Creeks. Marine Pollution Bulletin 85:204–213. **Testa J.M. et al. (2017)** Modeling Physical and Biogeochemical Controls on Dissolved Oxygen in Chesapeake Bay: Lessons Learned from Simple and Complex Approaches. In: Justic D., Rose K., Hetland R., Fennel K. (eds) Modeling Coastal Hypoxia. Springer

Appendix B: Workshop Participants

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